SEARCHES FOR SUPERSYMMETRY WITH THE CMS DETECTOR AT THE LHC*

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We review results of searches for physics beyond the Standard Model performed by the Compact Muon Solenoid detector at the Large Hadron Collider accelerator in proton–proton collisions at the center-of-mass energy of 7 TeV for data collected in 2011 and for the part of data at 8 TeV from 2012.

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1. Introduction

Recent precise measurements and the discovery of the Higgs boson [1] reaffirm the success of the Standard Model (SM) theory in the description of elementary particle interactions. However, in the wider view, the SM is not a completed model. An attractive approach is provided by the Supersymmetry (SUSY) [2], which implies the existence of new particles. In a natural way, contributions from SUSY particles can cancel SM divergences and radiative corrections, explaining why the Higgs boson has a mass at the weak scale, not at the Planck mass scale. SUSY allows the unification of gauge couplings and predicts the Dark Matter candidate. In general, SUSY can give an elegant solution to open questions of particle physics and, therefore, is widely searched at the LHC. The phenomenology of SUSY is rich and determined by an assumption of the supersymmetry breaking mechanism and a set of free model's parameters, which generate an unique SUSY mass spectrum and SUSY particle decay channels.

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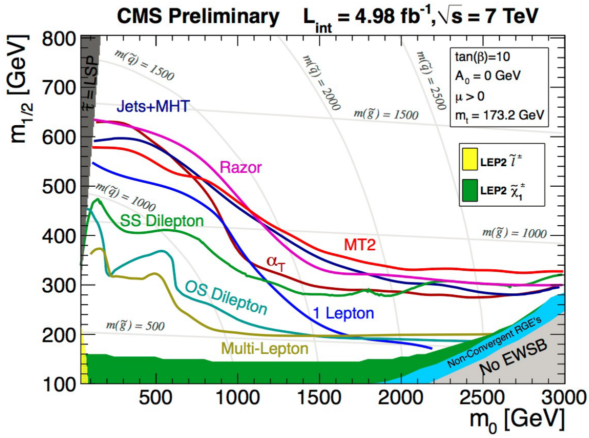
In this article, we present SUSY searches based on the data collected at the center-of-mass energy of 7 TeV and 8 TeV corresponding to 5–19 fb^{-1} of integrated luminosity stored by the CMS detector [3].

2. Initial supersymmetry searches

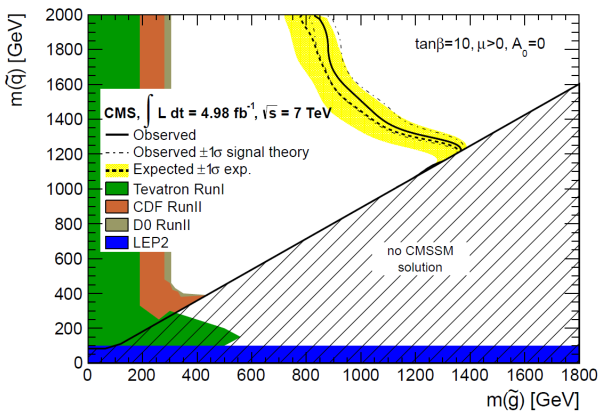
First searches have been performed for the popular model, the Minimal Supersymmetric Standard Model (MSSM). At the LHC, the SUSY production is dominated by the strong production of squarks and gluinos, which decay to quarks, gluons and other SM particles. If R-parity is conserved, SUSY decays end with a pair of lightest SUSY particles (LSP). In MSSM, the LSP is a neutral neutralino. Thus, SUSY signatures contain energetic jets and large missing transverse energy, MET, and may contain leptons and photons. Basic search channels include all hadronic final states (jets + MET) and signatures with one lepton (muon or electron), two leptons with the same (SS) or opposite sign (OS) or multi-lepton final states.

The summary of searches for supersymmetry [4] in different channels in the context of the Constrained MSSM (CMSSM) are shown in Fig. 1 (a). No significant excess of events above the expected backgrounds has been observed in 4.98 fb^{-1} of the full CMS data set collected at 7 TeV. The exclusion power is stronger for all hadronic channels, although it depends on specific kinematical observables used in analyses. The observed exclusion from the multi-jets analysis [5] is also presented in terms of squark and gluino masses and shown in Fig. 1 (b). Squark masses below 1.2 TeV and gluino masses below 800 GeV are excluded for the CMSSM framework. This analysis uses as a main discriminator a variable $\mathrm{MHT} = -\sum \vec{p}_{\mathrm{T}}$, where the sum is over jets with the transverse momentum $p_{\mathrm{T}} > 30\,\mathrm{GeV}$ and pseudo-rapidity $|\eta| < 5$.

The large space of CMSSM parameters has been excluded by direct searches and there was a need for a new general interpretation of SUSY search results, which can be used as reference and translated to different theoretical models. A framework of the Simplified Model Spectra (SMS) [6] was recently developed and it is used by both, ALTAS and CMS experiments for interpreting new results of searches for New Physics. SMS models assume a simple event topology for the production of a hypothetical sparticle. The final states are limited to a few particles and 2–3 body decay chains. Such topological signatures group large sectors of phase space of SUSY or non-SUSY models. Therefore, CMS SUSY analyses are interpreted in the framework of the simplified models.



(a)



(b)

Fig. 1. The CMS Observed 95% C.L. limits in the CMSSM $(m_0, m_{1/2})$ plane for remaining CMSSM parameters $\tan\beta = 10, \mu > 0, A_0 = 0$. (a) Results for several analyses shown for $4.98\,\mathrm{fb}^{-1}$ of integrated luminosity for $\sqrt{s} = 7\,\mathrm{TeV}$ data. (b) The mass limit on the $(m_{\tilde{g},}, m_{\tilde{q},})$ plane for the jets+MHT analysis.

3. All-hadronic SUSY search with α_T

All-hadronic searches have to deal with enormous background from the QCD jet production. One of the CMS inclusive searches [7] for supersymmetric processes with production of jets and MET in the final state is performed via a dimensionless kinematic variable, α_T, which can separate QCD events from SUSY events. In simplified case, for the event containing two jets

$$\alpha_\mathrm{T} = E_\mathrm{T}^{j_2}/M_\mathrm{T} = E_\mathrm{T}^{j_2}/\sqrt{H_\mathrm{T}^2 - \not{H}_\mathrm{T}^2}\,, \qquad (1)$$

where $E_{\mathrm{T}}^{j_2}$ is the less energetic jets from the di-jet system with transverse mass, M_{T}, calculated as a scalar sum of the transverse energy of jets, $H_{\mathrm{T}} = \sum_{i=1}^{N_{\mathrm{jet}}} E_{\mathrm{T}}$, and a magnitude of the vector sum of the transverse momenta of jets, $\not{H}_{\mathrm{T}} = |\sum_{i=1}^{N_{\mathrm{jet}}} \vec{p_{\mathrm{T}}}|$.

For a perfectly measured di-jet event with $E_{\mathrm{T}}^{j_1} = E_{\mathrm{T}}^{j_2}$, QCD jets are back-to-back in the limit of large jet momenta compared to their masses and value of α_{T} is 0.5. In the case of an imbalance in the measured transverse energy of back-to-back jets, α_{T} is smaller than 0.5 for QCD events with miss-reconstructed MET. When the two jets are not back-to-back and balancing MET, α_{T} is greater than 0.5, which is typical for SUSY events with genuine missing transverse energy from the escape of the LSP's pair. The variable α_{T} is usable also for events with more than two jets. An equivalent di-jet system is formed by combining all jets from a given event into two pseudo-jets, which parameters are used for calculations. Figure 2 illustrates this ability of the α_{T} to discriminate between multi-jet QCD events and all other SM or New Physics processes. The final selection with $\alpha_{\mathrm{T}} > 0.55$ makes the background QCD free. Hadronic events are selected from events with at least two jets satisfying $E_{\mathrm{T}} > 50$ GeV and $|\eta| < 3$. Next, events are vetoed if additional jets are present in the high eta region ($E_{\mathrm{T}} > 50$ GeV and $|\eta| > 3$) or when an isolated lepton or photon is found (lepton(γ) with $p_{\mathrm{T}} > 10(25)$ GeV). The pre-selection of events includes the trigger conditions, which require multiple jet final state and the loose criteria on discriminators α_{T} and H_{T}. The search is done in the bins of the H_{T} bins for values above $H_{\mathrm{T}} > 275$ GeV, as illustrated in Fig. 3 (a) and Fig. 4 (a). The SM background in H_{T} bins

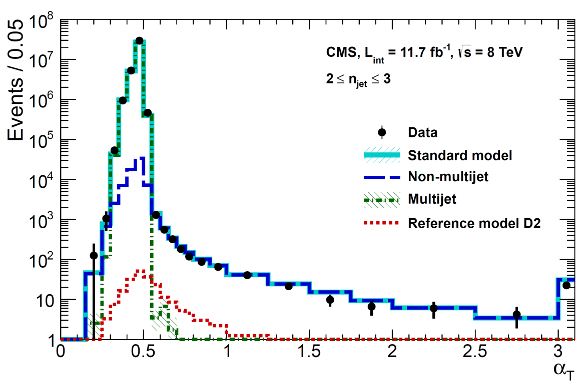
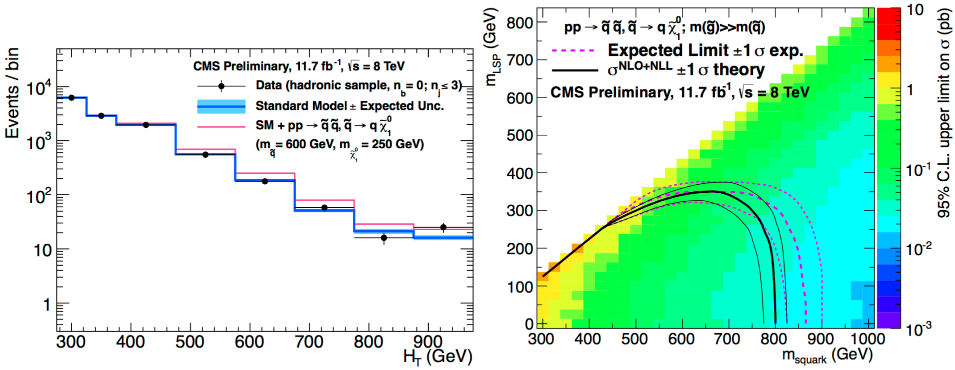
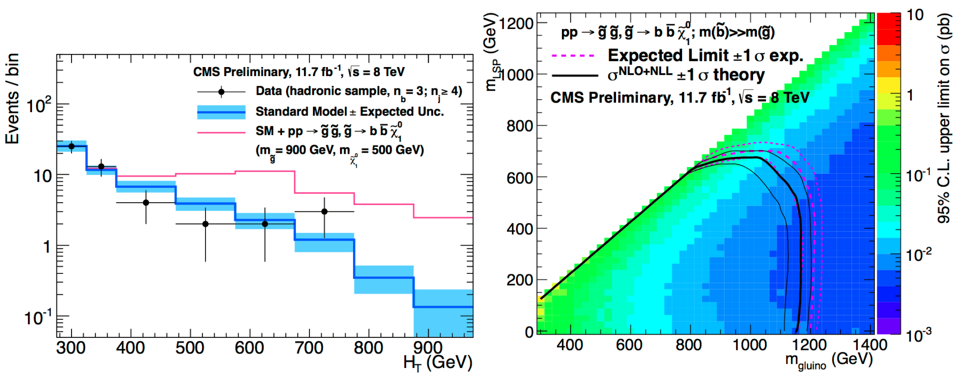


Fig. 2. The α_{T} distributions of events with $H_{\mathrm{T}} > 375$ GeV that satisfy all the selection criteria except the α_{T} requirement for the $2 \leq n_{\mathrm{jet}} \leq 3$ category. The data (solid circles), SM processes and the reference model (the bottom line) are shown. The last bin contains all events with $\alpha_{\mathrm{T}} > 3$.



(a) (b)

Fig. 3. (a) Event yields observed in data (solid circles) and SM expectations (line with band) in bins of H_T for the signal region when requiring zero b-quark jets and $2 \leq n_\mathrm{jet} \leq 3$. Expectations for the reference mass points of the signal model is superimposed on the SM-only expectations (thin line). (b) Observed upper limit on the production cross section at 95% C.L. as a function squark and LSP sparticle masses for the simplified model involving the direct production of first- and second-generation squarks. The black solid thick line indicates the observed exclusion assuming NLO+NLL SUSY production cross section. The black solid thin lines represent the observed exclusions when varying the cross section by its theoretical uncertainty. The dashed thick (thin) line indicates the median ($\pm 1\sigma$) expected exclusion.



(a) (b)

Fig. 4. As for Fig. 3, results for the simplified model involving the direct production of pair of gluino decaying to b-quarks. (a) The H_T distribution requiring exactly three b-quark jets and $n_\mathrm{jet} \geq 4$. (b) Observed upper limit on the production cross section at 95% C.L. as a function squark and LSP sparticle masses.

is estimated from a simultaneous binned likelihood fit to event yields in the signal region and control samples with jets, muons (μ+jets, $\mu\mu$+jets) and photon (γ+jets). All selected data is finally categorized according to the jet multiplicity and to the number of reconstructed jets identified as originating from bottom quarks. The categorization improves sensitivity of analysis to squark–squark, squark–gluino, and gluino–gluino production, including third-generation squarks.

An inclusive search with the α_{T} discriminator is based on a data sample of pp collisions collected at $\sqrt{s} = 8$ TeV, corresponding to an integrated luminosity of $11.7\,\mathrm{fb}^{-1}$. No significant excess of events over the Standard Model expectation is found. Exclusion limits are set in the parameter space of six simplified models. Two classes of SMS models are used. The first describes direct pair-production of squarks, including top and bottom squarks, that decay to a quark of the same flavour and the LSP. The second class describes gluino-induced production of squarks, in which gluino–gluino pair production is followed by the decay of each gluino to a quark–antiquark pair (including top and bottom squarks) and the LSP.

Observed upper limits on the production cross section at 95% C.L. are shown in Fig. 3 (b), Fig. 4 (b) and Fig. 5 in the context of simplified models. The strongest exclusions on gluino mass is about 1125 GeV for pair-produced gluinos each decaying to the LSP and pairs of sbottoms. For the direct pair production of squarks with their decay to a quark and the LSP, masses below 775 GeV are excluded (95% C.L.) for the first- and second-generation squarks. Bottom squark masses are excluded below 600 GeV.

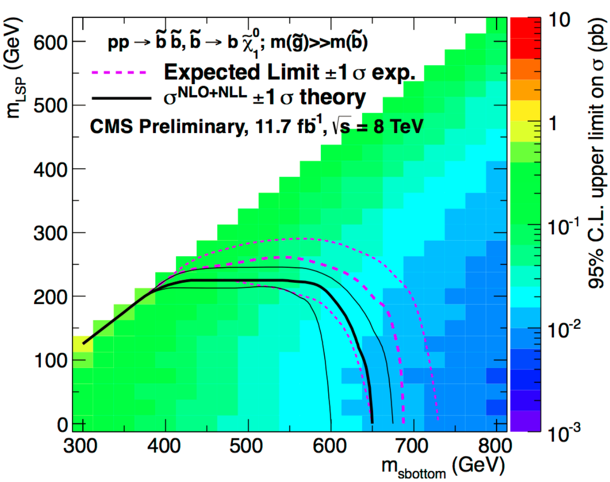


Fig. 5. As for Fig. 3, the observed upper limit on the production cross section at 95% C.L. as a function sbottom and LSP sparticle masses. The data subset includes events with one or two b-quark jets and $2 \leq n_{\mathrm{jet}} \leq 3$.

4. SUSY searches with the razor variables

An excellent ability of razor variables to search for supersymmetry was illustrated with the inclusive analysis [8] and the razor results are shown in Fig. 1 (a). The same method is applied to tau-enriched SUSY final states. The following search [9] is performed on data collected in 7 TeV pp collision with $4.7\,\mathrm{fb}^{-1}$ of integrated luminosity. Razor variables are design for the final state topology characteristic for R-parity conserved SUSY with an assumption that a pair produced squarks decay to the SM quark and invisible LSP, giving the final di-jet final state accompanied by the missing transverse energy. Long SUSY decays are reduced into the di-jet topology by grouping all jets and leptons (electrons and muons). The best combination with the smallest sum of mass squared of two new mega jets is used for further calculations.

Two mass-like razor variables, M_{R} and $M_{\mathrm{R}}^{\mathrm{T}}$, are calculated for the di-jet system using their four-momenta and the longitudinal and transverse components, $\vec{p}^{\,j_{i^{\mathrm{th}}}}$ as follows

$$M_{\mathrm{R}} = \sqrt{(|\vec{p}^{\,j_1}| + |\vec{p}^{\,j_2}|)^2 - \left(p_z^{j_1} + p_z^{j_2}\right)^2}\,, \tag{2}$$

$$M_{\mathrm{R}}^{\mathrm{T}} = \sqrt{\frac{\mathrm{MET}\left(p_{\mathrm{T}}^{j_1} + p_{\mathrm{T}}^{j_2}\right)^2 - \vec{\mathrm{MET}}\cdot\left(\vec{p}_{\mathrm{T}}^{\,j_1} + \vec{p}_{\mathrm{T}}^{\,j_2}\right)^2}{2}}\,. \tag{3}$$

The razor dimensionless ratio, R, describing a transverse shape of the event, is defined as

$$R = \frac{M_{\mathrm{T}}^{\mathrm{R}}}{M_{\mathrm{R}}}\,. \tag{4}$$

M_{R} is an equivalent of the mass difference between the directly produced sparticle and the LSP

$$R \equiv \frac{M_{\mathrm{Sparticle}}^2 - M_{\mathrm{LSP}}^2}{M_{\mathrm{Sparticle}}}\,. \tag{5}$$

A broad peak in the distribution of M_{R} is a clear signature of New Physics.

The tau-enriched SUSY search is performed for leptonic events, other events are rejected. Dedicated triggers require the presence of at least two jets with $p_{\mathrm{T}} > 56\,\mathrm{GeV}$ and one muon or electron with $p_{\mathrm{T}} > 10\,\mathrm{GeV}$, satisfying loose isolation criteria. At the triggering level, lower thresholds on the values of the variables R and M_{R} computed from on-line reconstructed jets and MET are applied. In the offline analysis, events with tightly-identified leptons (with $p_{\mathrm{T}} > 14\,\mathrm{GeV}$ and $|\eta_\mu| < 2.1$ or $|\eta_{\mathrm{elec}}| < 3.0$) are considered. Tau leptons identification is made with the dedicated technique in both hadronic and leptonic modes. The kinematic requirements on taus are $p_{\mathrm{T}} > 15\,\mathrm{GeV}$ and $|\eta| < 2.3$. Events are required to have at least two jets with $p_{\mathrm{T}} > 60\,\mathrm{GeV}$ and $|\eta| < 3.0$. All selected events are categorized into four exclusive subsets: 1$^{\mathrm{st}}$: MU–TAU box with $\tau \geq 1$ and $\mu \geq 1$ and $0\,e$, 2$^{\mathrm{nd}}$: MU box — all the other events without $\mu \geq 1$, 3$^{\mathrm{rd}}$: ELE–TAU box with $\tau \geq 1$ and $e \geq 1$ and $0\,\mu$, 4$^{\mathrm{th}}$: ELE box — all the other events without $e \geq 1$. Finally, cuts on razor variables are applied in all boxes $M_{\mathrm{R}} > 300\,\mathrm{GeV}$ and $0.11 < R^2 < 0.50$. In each box, *fit* and *signal regions* are defined as shown by the coloured rectangles in Fig. 6. *Fit regions* for relatively small M_{R} are used

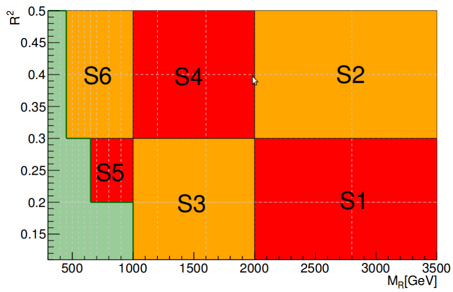
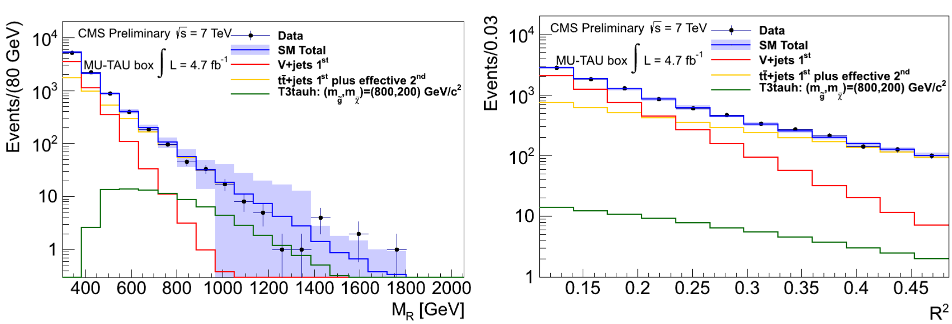


Fig. 6. The *fit* (for small M_{R}) and *signal* regions (Si$^{i=1-6}$) on the (M_{R}, R^2) plane used in the razor analysis.

to determine the shape of SM background which is extrapolated to the *signal region* for large M_{R}. *Signal regions* allow to find a signal as an excess on the 2D (M_{R}, R^2) tail by comparing the data and the expected background. Results of the unbinned maximum likelihood fit projected separately on M_{R} and R^2 are shown for the MU–TAU box in Fig. 7. No significant deviation



(a) (b)

Fig. 7. Distributions of M_{R} (a) and R^2 (b) after 2D fit for the MU–TAU box. Black points represent data. The histogram (with uncertainties shows as a band) is the total SM prediction from the fit. Other SM components are also displayed (as denoted on the legend). An example of signal for the simplified model is the bottom histogram.

from the SM expectation is observed in none of the boxes. Results are interpreted in a tau-enriched simplified model. In the final state, two taus are expected from the decay of a pair of gluinos. Additionally, four jets and MET from two neutrinos and two LSPs are present in the event. The model is studied as a function of the gluino and LSP mass. The mass of the intermediate invisible sparticle (neutral or charged) is fixed to half the gluino mass. Results for model with neutralino, $\tilde{\chi}_2^0$, exchange is shown in Fig. 8. The 95% confidence-level limit across the plane of the mass of gluino and the LSP is set.

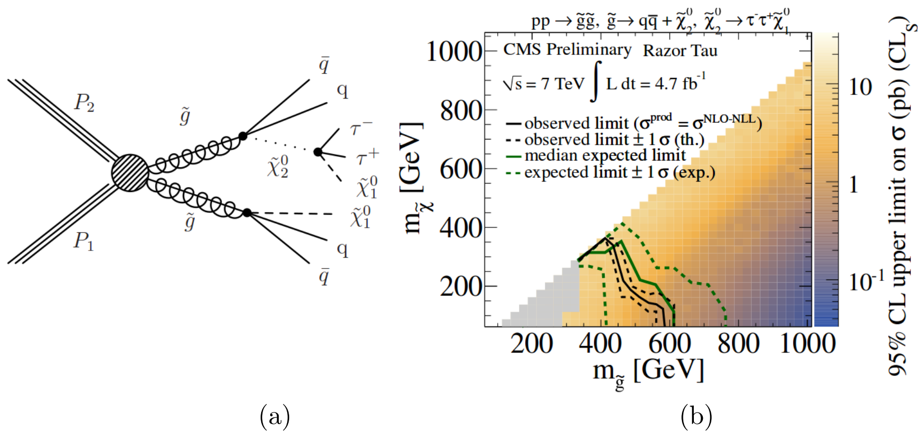


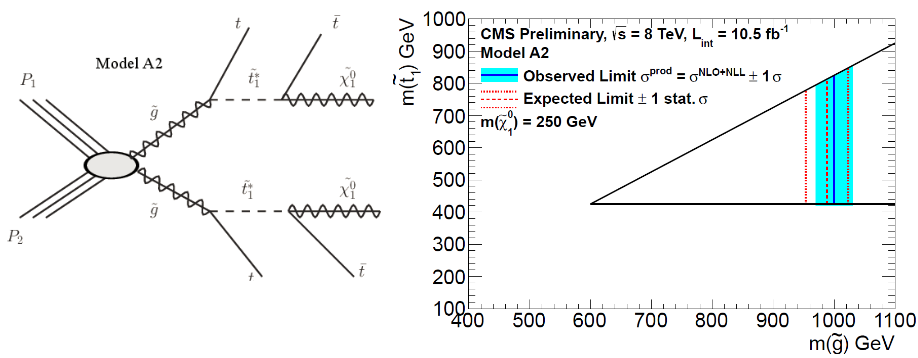
Fig. 8. Results for the simplified model T3tauh (a) as an exclusion cross section with respect to the model mass spectrum of gluino and LSP (b). The solid (dashed) lines show the observed (expected) limits. The color scale shows the model independent cross-section excluded in the SMS.

5. SUSY with top and bottom squarks

The same-sign di-lepton (electron or muon) events are extremely rare in the SM and by that, very sensitive to New Physics. In supersymmetry, such signatures arise scenarios with large mass splitting between the third generation of squarks and other squarks, resulting in final states reach in top and bottom quarks produced is SUSY cascade decays.

In the CMS analysis [10], events with the same-sign isolated di-leptons and two or more bottom-quark jets (b jets) are searched. A data set corresponding to an integrated luminosity of $10.5\,\text{fb}^{-1}$ of pp collisions at 8 TeV is used. Interesting events are collected with di-lepton triggers. In the next step, two isolated same-sign leptons ($p_T > 20\,\text{GeV}$ and $|\eta| < 2.4$) with pair invariant mass above 8 GeV, and at least two b-tagged ($p_T > 40\,\text{GeV}$ and $|\eta| < 2.4$) jets are selected. As main sources of the background are taken into account, miss-identified or non-prompt leptons (*fake leptons* coming, *i.e.*, from heavy-flavour decay, light-meson decay in flight or unidentified photon conversions and *charge flips* if electron charge is miss-reconstructed due to severe bremsstrahlung in the tracker material). The probability of such leptons is determined from data. The background from rare SM processes that yield the same-sign high-p_{T} leptons and b jets is obtained from the Monte Carlo simulation of the $t\bar{t}W/Z$ production.

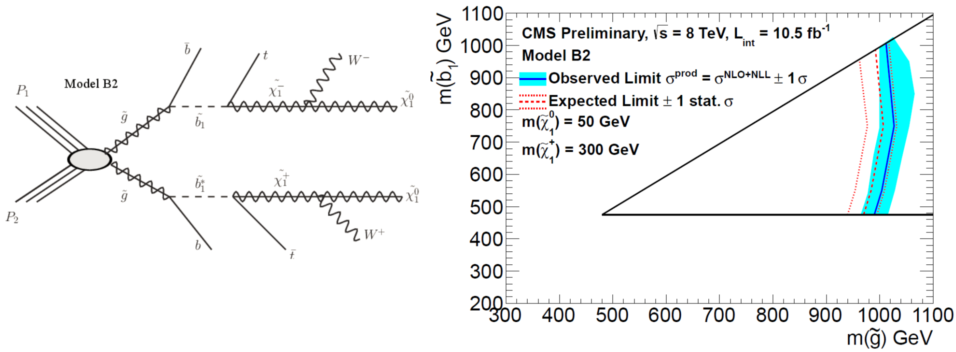
The search is performed in signal regions (SR) defined for the different number of b-tagged jets and different ranges of MET and H_{T} variables. Event yields and background predictions are compatible with each other in nine SRs. No excess over the SM is found. Therefore, limits on the number of events from the New Physics in each sample of SRs. These limits are then translated into a limit on the same-sign top-pair production cross section and are used to bound the parameters of SUSY simplified models with third-generation squarks. In Fig. 9 and Fig. 10, the exclusion results are shown for SUSY models in which the pair produced gluinos decay thought stop or sbottom squarks, respectively. The analysis allows to exclude gluinos with masses up to approximately 1 TeV. Moreover, a lower limit on the bottom-squark mass of 450 GeV is set. More results are presented in the original publication [10].



(a) (b)

Fig. 9. Results for the same-sign di-lepton search for the drawn simplified model (a). Exclusion regions at 95% C.L. in the plane of stop and gluino masses (b). The additional mass parameters of the model are given on the plot. The black lines represent the kinematic boundaries of the models. The excluded regions are those within the kinematic boundaries and to the left of the bands.

The light stop quarks are motivated by SUSY models solving in a *natural* way the gauge hierarchy problem. At CMS, the stop pair production is search [11] with a single isolated lepton (electron or muon), jets, and large MET. The 8 TeV data sample used corresponds to an integrated luminosity



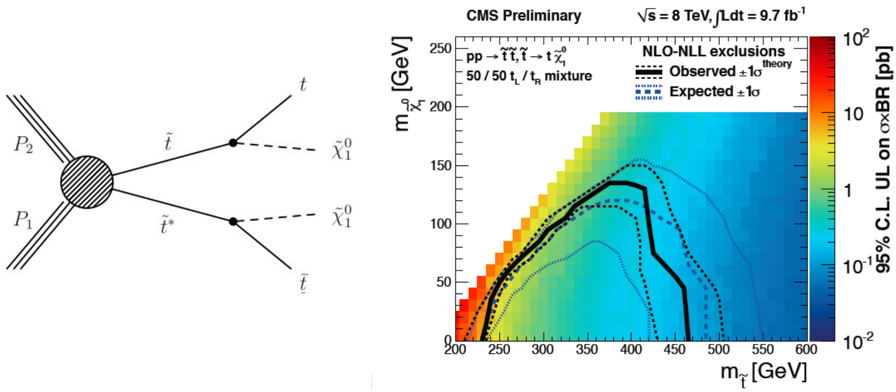
(a) (b)

Fig. 10. As for Fig. 9, exclusion limits for the drawn simplified model (a) on the plane of sbottom and gluino masses (b).

of $9.7\,\mathrm{fb}^{-1}$ collected in 2012. The data was collected using single high-p_{T} electron and muon triggers and additionally with di-lepton triggers to control $t\bar{t}$ background. Selected events are required to have an isolated lepton with $p_{\mathrm{T}} > 30\,\mathrm{GeV}$ and $|\eta| < 1.4$ for electrons and $|\eta| < 2.1$ for muons, at least four jets ($p_{\mathrm{T}} > 30\,\mathrm{GeV}$ and $|\eta| < 2.5$) and moderate missing transverse energy ($\mathrm{MET} > 50\,\mathrm{GeV}$). At least one of the jets is required to be identified as originating from a b-quark and events are required to have large transverse mass, $M_{\mathrm{T}} > 120\,\mathrm{GeV}$, which is defined as

$$M_{\mathrm{T}}^2 = 2p_{\mathrm{T}}^{\mathrm{lep}}\,\mathrm{MET}\,(1 - \cos(\Delta\phi))\,, \tag{6}$$

where $\Delta\phi$ is the azimuthal angle between the lepton and MET direction. The SM background arises from semi-leptonic processes of $t\bar{t}$ and W+jets production. SM event yields are estimated form the data control samples and Monte Carlo simulations. Finally, the search is performed separately in signal regions defined by M_{T} and MET requirements. No significant excess in data is observed above the expected SM backgrounds. The results are interpreted in the context of simplified models of top squark pair production, where the top squarks decay either to a top quark and a neutralino or to a bottom quark and a chargino. In Fig. 11, the exclusion limit on the production cross section of stop decaying to neutralino. Depending on the decay mode, the results probe top squarks with masses in the range of 160–430 GeV.



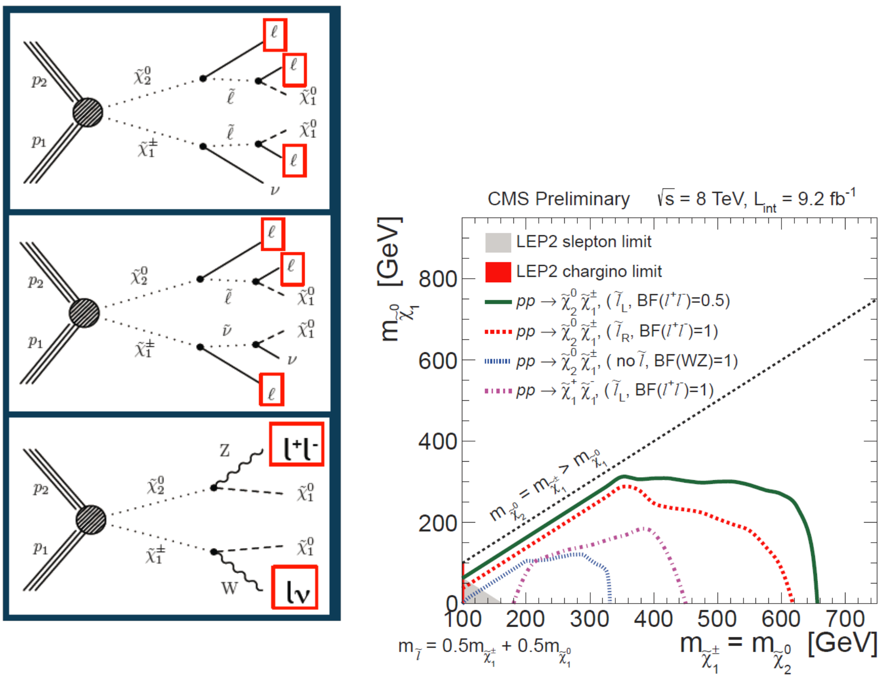
(a) (b)

Fig. 11. Results for the top squark pair production model (a). The exclusion limits on the signal cross section are shown on the mass plane of stop and neutralino (b). The shading indicates the upper limit. A set of exclusion contours is indicated assuming NLO–NLL cross sections.

6. Electroweak production of charginos, neutralinos and sleptons

The next CMS search [12] for supersymmetry is motivated by the electroweak (EWK) production of charginos, neutralinos and sleptons. In that case, a low hadronic activity in the event is expected. Therefore, the EWK-like SUSY events possibly would be missed in all-hadronic searches described above. It is expected that charginos and neutralinos can have significant decay branching fractions to leptons or on-shell vector bosons, yielding multi-lepton final states. Similarly, slepton pair production gives rise to final states with leptons. In the analysis, different lepton multiplicities are studied to consider diverse final states. The $9.2\,\mathrm{fb}^{-1}$ data sample collected at 8 TeV collisions in 2012 was used. The triggering is mainly done with single lepton triggers.

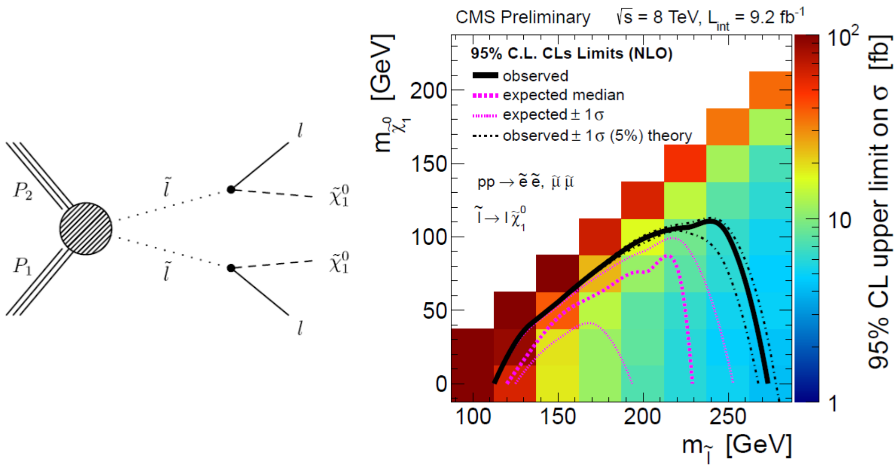
The final state with exactly three leptons is characteristic for the ($\tilde{\chi}^0_2$–$\tilde{\chi}^\pm_2$) neutralino–chargino production as illustrated in Fig. 12 (a). In this search, leptons (electrons and muons with $p_{\mathrm{T}} > 10\,\mathrm{GeV}$) and taus decaying leptonically (τ with $p_{\mathrm{T}} > 20\,\mathrm{GeV}$), all within $|\eta| < 2.4$ are used. The main SM backgrounds are from WZ and $t\bar{t}$ production, giving tree isolated leptons. For the top production, a third non-prompt lepton is misidentified as prompt. Events are required to have MET $> 50\,\mathrm{GeV}$. The presence of jets (with $p_{\mathrm{T}} > 40\,\mathrm{GeV}$) in the event is checked. In the case of the identification of jet as a b-quark jet, events are rejected. The search is performed for events with an opposite-sign-same-flavour (OSSF) lepton pair and the third lepton, which is either an electron or a muon. For the OSSF pair, the mass invariant, M_{ll}, is calculated. The transverse momentum of the remaining lepton is used to calculate the transverse mass M_{T}, accordingly to Eq. (6). Selected events are classified into exclusive *bins* depending on their values of M_{ll}, MET and M_{T}. In each bin, the SM background contributions are predicted from MC simulation and data driven methods and compared with the observed data. The observed event rates remain in agreement with expectations from the SM. These results are used to set limits on the direct production of neutralino–chargino within several models. In Fig. 12, results from the three lepton with OSSF search are shown together with limits from other variants analysis.



(a) (b)

Fig. 12. Summary of results for chargino–neutralino production with decays to left-handed sleptons, right-handed sleptons, or direct decays to vector bosons, and chargino-pair production. Three lepton search with OSSF pairs (a) gives 95% exclusion limits for channels denoted on the plot.

From the same analysis, the other interesting results come from the search with non-resonant opposite-sign (OS) di-leptons. Final states with oppositely charged ee, $e\mu$, or $\mu\mu$ are considered, where both leptons must have $p_{\mathrm{T}} > 20\,\mathrm{GeV}$. The ee and $\mu\mu$ invariant mass must differ from the Z boson mass by at least 15 GeV. Events are selected with MET $> 50\,\mathrm{GeV}$. As a main discriminator, kinematical variable $M_{\mathrm{CT}\perp}$ [13] is used to control the remaining SM background from $t\bar{t}$ and WW production. Results from the OS di-leptons search are sensitive to the direct production of sleptons. As shown in Fig. 13, slepton masses are probed up to 275 GeV.



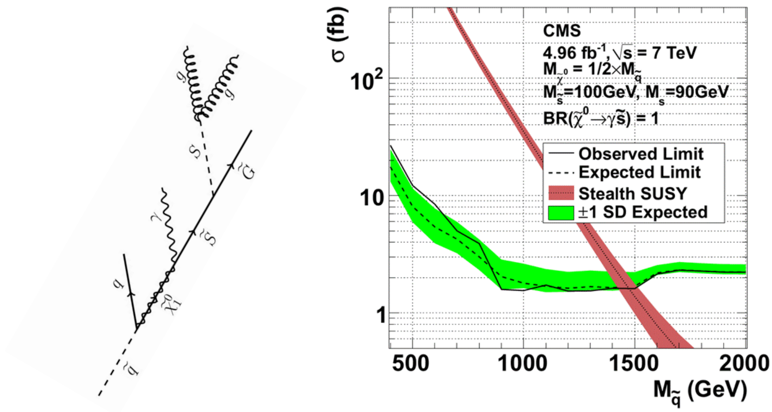
(a) (b)

Fig. 13. The model of the slepton production and the decay (a). Limits on slepton pair production cross section times branching ratio for decaying sleptons.

Summarizing, the analysis explored final states with three leptons, four leptons, two same-sign leptons, two resonant OSSF leptons plus two jets, and two non-resonant OS leptons. In none of signatures, excesses above the SM expectations were observed. The results are used to exclude a range of chargino, neutralino, and slepton masses, with assumption of large branching fractions to leptons and vector bosons.

7. Stealth SUSY

Supersymmetric models, called *stealth* SUSY, naturally produce signatures of low MET without special tuning of masses. The simplest stealth SUSY models have a low energy scale of SUSY breaking and a new hidden sector. In a visible sector, a standard R-parity conserved decays occur of the squark decaying to the SM quark and the LSP. The LSP plays a new role as the lightest visible sector SUSY particle (LVSP). With the existence of the hidden sector the LVSP decays into a lighter hidden sector SUSY particle, a signlino $\tilde{S}$ and its SM partner (γ for bino-like LVSP). In the subsequent decay of the singlino particle to its invisible SM partner, S, and the true LSP, $\tilde{G}$, the near mass degeneracy leaves little phase space for the true LSP to carry momentum. The decay of particle S can be visible as a pair of gluons. Schematically, the decay of a squark in stealth SUSY is shown in Fig. 14. The resulting signature of the stealth SUSY is a final state with two photons and four jets and low MET.



(a) (b)

Fig. 14. Decay of a squark in stealth SUSY (a) and the related cross-section limit at the 95% C.L. as a function of squark mass.

At the CMS, the search [14] is performed for the 2011 data set of 4.96 fb^{-1} integrated luminosity. The signal is searched in events with at least two photons (with $p_T > 40, 25$ GeV, respectively), at least 4 jets ($p_T > 20$ GeV) and MET > 20 GeV. The main SM background comes from QCD production of $2\gamma+ \geq 4$ jets (QCD). It is estimated from the data based on the observation that the shape of the S_T (where $S_T = \sum_{i=1}^{N_{\text{jet}}} p_T + \sum_{i=1}^{N_\gamma} p_T$ + MET) spectrum of the SM background is independent of jet multiplicity. No excess have been found in the signal regions. Therefore, the exclusion limits on squark mass were set as illustrated in Fig. 14. In the context of stealth SUSY, squark masses below 1430 GeV are excluded at the 95% confidence level.

8. Gauge mediated SUSY

The high theoretical interest for a New Physics is put on models with the gauge mediated supersymmetry breaking (GMSB). In GMSB models, the LSP is light gravitino ($\tilde{G}$) and a key role is played by the next-to-lightest SUSY particle (NLSP), which determine the signature of the SUSY signal. The CMS has performed searches in whose the NLSP is the lightest neutralino ($\tilde{\chi}_2^0$) or slepton stau ($\tilde{\tau}_1$).

8.1. NLSP neutralino

In the first analysis [15], final states with photons and missing transverse energy are considered. Topologies with one or two photons are studied. The SM background, mainly QCD is estimated from the control samples. In the signal regions, distribution of MET are compared with spectra expected from the SM processes. The search with at least one photon (with $p_{\mathrm{T}} > 80\,\mathrm{GeV}$) plus at least two hadronic jets (with $p_{\mathrm{T}} > 30\,\mathrm{GeV}$) and high MET ($> 100\,\mathrm{GeV}$) can be interpreted in the framework of the General Gauge Mediated (GGM) models with the NLSP bino-like or wino-like neutralino. No excess of events at high MET is observed for the CMS data of $4.04\,\mathrm{fb}^{-1}$ of pp collisions at $\sqrt{s} = 8\,\mathrm{TeV}$. The $\mathrm{CL_S}$ method is used to determine 95% C.L. upper limits for the squark *versus* gluino mass plane from 400 to 2000 GeV in squark and gluino mass with the neutralino mass set again at 375 GeV. In Fig. 15, the exclusion contours are shown for both, bino- and wino-like, types of neutralino.

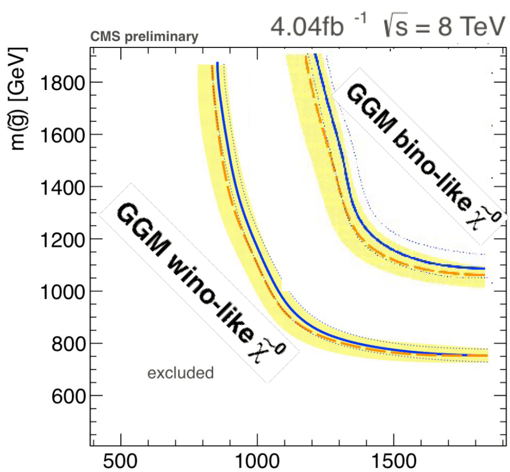


Fig. 15. Results for the GGM for the single photon analysis. 95% C.L. exclusion contours on the signal cross section in gluino–squark mass space for a 375 GeV bino-like and wino-like neutralino. The shaded uncertainty band around the exclusion contours correspond to the NLO renormalization and PDF uncertainties of the signal cross section.

8.2. NLSP stau

An exotic event topology is expected for the case of the stau NLSP. Depending on the GMSB model parameters, stau can be a long-lived particle. The detection of such particle, which is like a massive muon, requires the implementation of special measurement techniques. In the CMS, the detector signatures under study are a long time-of-flight (TOF) to the outer muon system and an anomalously high (or low) energy deposition (dE/dx) in the inner tracker. Measurements of TOF and dE/dx compared with the particle momentum (p) allow to determine a mass of the hypothetical particle. Recent CMS analysis [16] is performed for data collected in 2011 and 2012 in collision at $\sqrt{s} = 7$ and 8 TeV. Analysis results are presented for various combinations of signatures in the inner tracker only, inner tracker and muon system, and muon system only. The data are consistent with the expected background and limits on the cross section for production of long-lived particles are set, as shown in Fig. 16. Among different results, limits on staus (GMSB) from the cascade decays and pair produced stau are set. The obtained mass lower limit at 95% C.L. on GMSB staus from cascade decays is 440 GeV. For pair produced staus, masses of stau below 330 GeV are excluded.

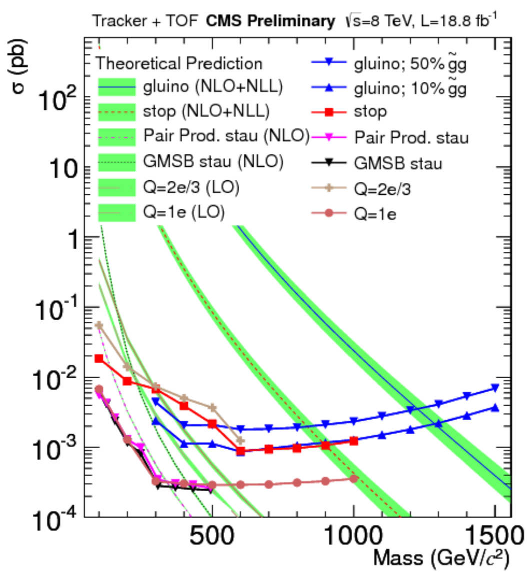


Fig. 16. Cross section upper limits at 95% C.L. on various signal models for the tracker+TOF analysis looking for long-lived particles. Staus from the cascade decays and from the direct production are indicated by lines with inverted triangles.

9. Conclusions

The CMS has performed a large set of inclusive searches with different signatures and the detection methods. No evidence of sparticle production have been found. Therefore, the exclusion limits on masses of SUSY particles have been set in the context of CMSSM and more generalized formalism of SMS models. With the half of the pp data collected at center-of-mass energy 8 TeV at 2012, masses of gluino and squarks of the first and the second generation were excluded below about 1–1.5 GeV, depending on the assumption about the model. Also sbottom and stop masses were probed up to about 650 GeV and 430 GeV, respectively. The CMS established mass limits on the chargino–neutralino production, reaching mass up to 650 GeV. Also the first limit on the direct production of slepton pair was set. Slepton masses below 275 GeV were excluded.

Through the wide range of possible signatures, supersymmetry has many ways to hide. It makes searches challenging and interesting. The motivation for SUSY is strong. Consequently, even more effort will be put into searches for supersymmetry in the near future.

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REFERENCES

[1] CMS Collaboration, *Phys. Lett.* **B716**, 30 (2012).
[2] S.P. Martin, `arXiv:hep-ph/9709356`.
[3] CMS Collaboration, *JINST* **3**, S08004 (2008).
[4] `https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS`
[5] CMS Collaboration, *Phys. Rev. Lett.* **109**, 171803 (2012).
[6] J. Alwall, P. Schuster, N. Toro, *Phys. Rev.* **D79**, 075020 (2009).
[7] CMS Collaboration, `arXiv:1303.2985 [hep-ex]`.
[8] CMS Collaboration, `arXiv:1212.6961 [hep-ex]`.
[9] CMS Collaboration, CMS-SUS-11-029, 2012.
[10] CMS Collaboration, *J. High Energy Phys.* **03**, 037 (2013).
[11] CMS Collaboration, CMS-SUS-12-023, 2012.
[12] CMS Collaboration, CMS-SUS-12-022, 2012.
[13] K.T. Matchev, Myeonghun Park, *Phys. Rev. Lett.* **107**, 061801 (2011).
[14] CMS Collaboration, *Phys. Lett.* **B719**, 42 (2012).
[15] CMS Collaboration, CMS-SUS-12-018, 2012.
[16] CMS Collaboration, CMS-EXO-12-026, 2013.